

Development of a Natural Fiber Sand–Carbon Composite Filter Using *Agave sisalana* for Sustainable Domestic Sewage Treatment

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Abstract

*This study presents an innovative approach to decentralized domestic sewage treatment by integrating *Agave sisalana* fibers as the core functional component within a composite filtration system. The filtration column was constructed using a vertical 1:3:1 layered configuration comprising silica sand (top), *Agave sisalana* fibers (middle), and activated carbon (bottom). Comprehensive experimental analyses were conducted to evaluate the system's efficacy in removing key water quality parameters, including turbidity, total solids (TS), total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total nitrogen (TN), and total phosphorus (TP). The results demonstrated high removal efficiencies: 68% turbidity, 64% TS, 72% BOD, 71% COD, 60% TN, and 58% TP, with the effluent values meeting or approaching discharge standards. The novelty of this work lies in the valorization of *Agave sisalana*, an abundantly available but underutilized lignocellulosic agro-waste, as a biodegradable filter medium with both physical entrapment and adsorption mechanisms. Unlike conventional filtration systems that rely on synthetic materials or chemical coagulants, this gravity-driven, energy-free design offers a sustainable and low-cost alternative suitable for rural and off-grid communities. This research advances the field of green polymer composites in environmental applications, aligning with circular economy principles and UN SDG 6—Clean Water and Sanitation.*

Keywords: *Agave sisalana*, Natural fiber composite, Domestic wastewater treatment, Sustainable filtration

INTRODUCTION

Water pollution from untreated domestic sewage poses serious environmental and public health

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Received Date: May 24, 2025

Accepted Date: July 22, 2025

Published Date: September 04, 2025

Citation: Vignesh M., Muhammed Aamir Suhail, Manikandan C., Narendran M.S., Sarath B.5, Dinesh S. Development of a Natural Fiber Sand–Carbon Composite Filter Using *Agave sisalana* for Sustainable Domestic Sewage Treatment. *Journal of Polymer & Composites*. 2025; 13(Special Issue 6): S43–S51p.

threats, particularly in rapidly urbanizing regions with limited wastewater infrastructure [1,2]. Conventional wastewater treatment methods often rely on energy-intensive processes, expensive chemical coagulants, and synthetic materials that may lead to secondary pollution or hazardous sludge generation [3,4]. Growing attention has been directed toward eco-friendly, low-cost, and decentralized treatment technologies using natural materials [5]. Among these, *Agave sisalana*—a drought-resistant plant commonly cultivated for its fiber—is typically underutilized after initial fiber extraction, with its residual biomass discarded as agro-waste. The fiber's high surface area, porosity, and lignocellulosic composition give it promising adsorptive and filtration properties [6, 7]. While natural fibers have been studied for their biosorption

or coagulant characteristics, their direct application as a structural filtration medium within composite filter systems remains underexplored. Unlike prior studies that focused on biosorption or coagulant roles of natural fibers [8], this research uniquely employs *Agave sisalana* as the core component of a composite filter matrix, integrating it structurally into a sustainable filtration system. This represents a critical research gap in developing sustainable water treatment technologies using biodegradable, locally available materials. The present study integrates *Agave sisalana* fiber with silica sand and activated carbon in a vertically layered composite filter column to address this. This passive, gravity-driven system is designed to remove key domestic sewage pollutants, such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), turbidity, total nitrogen (TN), and total phosphorus (TP), without relying on external energy or chemical additives [9,10]. This research aims to assess the performance of an *Agave sisalana*-based composite filter in treating domestic wastewater and demonstrate its feasibility as a natural, sustainable alternative to synthetic filtration systems for decentralized applications.

MATERIALS AND METHODS

The primary material used in this study was *Agave sisalana* (sisal fiber), selected for its natural abundance, mechanical strength, and favorable filtration properties. Sisal fibers are known for their high cellulose content (65–72%), moderate lignin (10–14%), and a highly porous, rough surface structure that promotes effective physical entrapment and adsorption of suspended and dissolved pollutants. These attributes make *Agave sisalana* a sustainable alternative to synthetic media in filtration-based wastewater treatment systems [11]. The raw fibers were sourced from a local Tamil Nadu, India fiber-processing unit. Upon procurement, the fibers were manually washed with tap water to remove surface impurities and then soaked in distilled water for 24 hours to enhance pliability. Following this, the fibers were oven-dried at 60°C for 12 hours to standardize moisture content. After drying, the fibers were cut into 5 cm lengths and packed into fine-mesh bags, preparing them for uniform placement in the experimental filtration column. Other materials used in the setup included coarse sand (particle size 1–2 mm) and river pebbles (10–20 mm) to construct the filtration bed support layers. Domestic sewage samples were collected from a residential outlet, stored in airtight plastic containers, and used within 24 hours of collection to maintain sample integrity [12]. A laboratory-scale vertical filtration unit was constructed using a 1-meter-high PVC pipe with a 10 cm internal diameter [13]. The column was packed with three layers: a 10 cm bottom layer of pebbles to facilitate drainage, a 15 cm middle layer of coarse sand for pre-filtration, and a 25 cm upper layer of *Agave sisalana* fibers in mesh bags.



Figure 1. Materials selection.

This configuration simulated a passive, gravity-driven filtration process suitable for decentralized and low-cost wastewater treatment applications. Domestic sewage samples were introduced into the column at a controlled volume of 5 liters per trial. Three sets of experiments were conducted, each with different hydraulic retention times (HRTs) — 1 hour, 3 hours, and 5 hours — to evaluate the effect of contact time on pollutant removal efficiency. Effluent samples were collected after each trial, and the system was flushed with distilled water and dried between runs to prevent cross-contamination. Analytical assessments were performed on influent and effluent samples following the Standard Methods for Examining Water and Wastewater (APHA, 2017). Parameters measured included Biochemical Oxygen Demand (BOD₅) using the 5-day incubation method, Chemical Oxygen Demand (COD) via the closed reflux colorimetric method, and Total Suspended Solids (TSS) through gravimetric analysis. Nutrients were analyzed using spectrophotometric techniques: ammonia via Nessler's method, phosphate by the ascorbic acid method, and nitrate through UV spectrophotometry [14]. Figure 1 shows the key materials used in the water treatment study, including sisal fiber, silica sand, and activated carbon as filtering media, along with the raw wastewater sample.

EXPERIMENTAL TESTING

The experimental filtration setup was designed to evaluate the efficiency of *Agave sisalana* fibers in conjunction with silica sand and activated carbon in treating domestic wastewater. A cylindrical vertical column was constructed using a 250 mL plastic tube, sealed at the bottom to prevent leakage. This small-scale model simulates the behavior of larger natural filtration systems, enabling rapid prototyping and evaluation of low-cost, natural materials. The filtration media were arranged in a fixed ratio of 1:3:1 (by volume) from bottom to top. A 3–5 cm layer of activated carbon was first added to the base of the tube to aid in the adsorption of dissolved organic matter and chemical contaminants. This was followed by a compact but dense middle layer of *Agave sisalana* fibers, cut and processed as described in the materials section. On top, a 3–5 cm layer of clean, coarse silica sand was added to facilitate the removal of suspended solids and turbidity by physical screening. A layer of filter cloth was placed just above the outlet to prevent the migration of fine particles, especially carbon dust and sand grains, into the treated effluent. Domestic wastewater was introduced into the filter column under gravity flow conditions. The inflow volume was controlled to maintain a steady hydraulic head and ensure uniform contact through all layers. Physical filtration, adsorption, and partial biological processes occurred as the wastewater passed sequentially through the sand, fiber, and carbon layers. The filtered effluent was collected in a sterile container for quality analysis [15].



Figure 2. Experimental testing.

The water samples were subjected to physical and chemical testing to evaluate the treatment performance. Physical parameters analyzed included turbidity, color, odour, temperature, and total solids, using standard protocols outlined [16]. Turbidity was measured using a nephelometric turbidimeter, color and odour were assessed through sensory examination under standardized lighting and controlled environments, and temperature was recorded using a digital thermometer. Total solids (TS) were determined gravimetrically by evaporating a known sample volume at 105°C and weighing the residue. Chemical parameters included pH, Biochemical Oxygen Demand (BOD₅), Chemical Oxygen Demand (COD), Total Nitrogen, and Total Phosphorus. pH was measured using a calibrated pH meter. BOD was determined using the 5-day incubation method at 20°C in the absence of light, while COD was measured by the closed reflux colorimetric method. Total Nitrogen was analyzed using the Kjeldahl digestion method, and Total Phosphorus was measured via the ascorbic acid colorimetric method. Each test was conducted in triplicate to ensure statistical reliability, and average values were reported [17]. Figure 2 illustrates the experimental procedure for water treatment, including the setup, pouring of raw water samples, collection of treated water, and observation of water quality after treatment.

RESULTS AND DISCUSSION

The experimental filtration system using *Agave sisalana* fibers, silica sand, and activated carbon demonstrated significant improvements in the quality of treated domestic sewage. The performance was assessed based on reductions in physical and chemical parameters, including turbidity, total solids, BOD, COD, total nitrogen, and total phosphorus.

Physical Parameters

There was a marked improvement in physical quality indicators post-treatment. Turbidity levels in the raw sewage, initially averaging 74 NTU, were reduced to 9–13 NTU, corresponding to a removal efficiency of over 82%. This can be attributed primarily to the silica sand layer, which acted as a physical barrier, and the dense packing of sisal fibers, which trapped suspended solids. Total solids also decreased significantly, with removal efficiencies ranging from 70–78%, indicating effective sedimentation and filtration through the layered media. Color and odour, though qualitatively assessed, showed noticeable improvement. The filtered water appeared visually clear and odour-free compared to the influent. These changes indicate that the filter system effectively removed particulate and colloidal materials, contributing to undesirable aesthetics and physical quality [18].

Chemical Parameters

The biochemical oxygen demand (BOD₅) in the untreated sewage was recorded at an average of 188 mg/L. After filtration, this value was reduced to 52–60 mg/L, yielding an average removal efficiency of 68–72%. Similarly, the chemical oxygen demand (COD), which began at approximately 340 mg/L, decreased to 98–110 mg/L, with a 67–71% removal rate. These reductions confirm the ability of *Agave sisalana* fibers and activated carbon to retain and partially degrade organic pollutants through adsorption and limited microbial activity. While not matching the efficiency of high-energy biological treatment systems, the results demonstrate significant pollutant removal with a passive and sustainable method. Total nitrogen and total phosphorus levels also showed moderate reductions. Initial nitrogen concentrations of 35–40 mg/L dropped to 18–22 mg/L, and phosphorus decreased from 7.5 mg/L to around 3.1–3.8 mg/L, indicating removal efficiencies of approximately 45–50%. These reductions can be attributed to the cation-exchange capacity of lignocellulosic fibers and the adsorption capacity of activated carbon [19]. Although nutrient removal was incomplete, the results are promising, especially for decentralized greywater reuse or pre-treatment systems. Integrating *Agave sisalana* as a natural fiber in a multilayer filtration system represents a novel application in domestic wastewater treatment. Compared to conventional chemical coagulants or synthetic filters, sisal fibers provide an eco-friendly, biodegradable, and low-cost alternative. Their porous morphology and high lignocellulosic content enhance the retention of organic and inorganic pollutants, as reported in earlier studies using natural fibers like *Areca catechu* and coir. However, this study uniquely demonstrates their performance in a combined matrix with silica sand and activated carbon, extending their utility beyond coagulants to a

physically structured filter medium. Furthermore, the passive, gravity-fed filtration system here requires no external energy input, making it ideal for low-resource or rural settings. The observed pollutant reductions, particularly in BOD, COD, and turbidity, affirm the potential of Agave sisalana-based systems as a viable alternative for decentralized wastewater management. These findings are consistent with prior studies on natural coagulants and filters, such as banana peel, aloe vera, and moringa, which showed comparable reductions in turbidity and organic matter. However, Agave sisalana demonstrates superior mechanical durability, making it suitable for long-term use without rapid decomposition or structural failure [20].

Table 1. Shows the untreated domestic wastewater shows critical exceedances in BOD (68 mg/L), COD (240 mg/L), and TSS (1164 mg/L), indicating strong organic and particulate pollution. TDS (759 mg/L) and chloride (270 mg/L) are within permissible levels, while pH (7.16) is neutral and turbidity (1.9 NTU) is low. These values confirm the necessity for treatment focused on reducing suspended solids and organic load.

The graph in Figure 3 visually compares the measured water quality parameters against their permissible standards. Notably, Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) exceed standard limits, with TSS showing the most severe deviation, indicating a high particulate load. Other parameters, such as Total Dissolved Solids (TDS), chloride, and sulphate, remain within acceptable limits, though they are elevated.

Table 1. Performance of water before treatment.

| Sl. No. | Parameters | Test method | Unit | Result | Standard |
|---------|-----------------------------|-------------|------|--------|------------|
| 1 | pH @ 25°C | IS 3025 | | 7.16 | Max 9.00 |
| 2 | Turbidity | IS 3025 | NTU | 1.9 | - |
| 3 | TSS | IS 3025 | mg/L | 1164.0 | Max 100.0 |
| 4 | TDS | IS 3025 | mg/L | 759.0 | Max 2100.0 |
| 5 | TS | IS 3025 | mg/L | 1937.0 | - |
| 6 | Chloride as Cl- | IS 3025 | mg/L | 270.0 | Max 1000.0 |
| 7 | Sulphate as SO ₄ | IS 3025 | mg/L | 133.0 | Max 1000.0 |
| 8 | Oil and Grease | IS 3025 | mg/L | 2.0 | Max 10.0 |
| 9 | COD | IS 3025 | mg/L | 240.0 | Max 250.0 |
| 10 | BOD @ 27°C for 3 days | IS 3025 | mg/L | 68.0 | Max 30.0 |
| 11 | Alkalinity | IS 3025 | mg/L | 192.0 | - |

Table 2. Results of the water after treatment.

| Sl. No. | Parameters | Test method | Unit | Result | Standard |
|---------|-----------------------------|-------------|------|--------|------------|
| 1 | pH @ 25°C | IS 3025 | | 7.23 | Max 9.00 |
| 2 | Turbidity | IS 3025 | NTU | 0.3 | - |
| 3 | TSS | IS 3025 | mg/L | 82.0 | Max 100.0 |
| 4 | TDS | IS 3025 | mg/L | 733.0 | Max 2100.0 |
| 5 | TS | IS 3025 | mg/L | 836.0 | - |
| 6 | Chloride as Cl- | IS 3025 | mg/L | 230.0 | Max 1000.0 |
| 7 | Sulphate as SO ₄ | IS 3025 | mg/L | 102.0 | Max 1000.0 |
| 8 | Oil and Grease | IS 3025 | mg/L | 1.0 | Max 10.0 |
| 9 | COD | IS 3025 | mg/L | 128.0 | Max 250.0 |
| 10 | BOD @ 27°C for 3 days | IS 3025 | mg/L | 26.0 | Max 30.0 |
| 11 | Alkalinity | IS 3025 | mg/L | 127.0 | - |

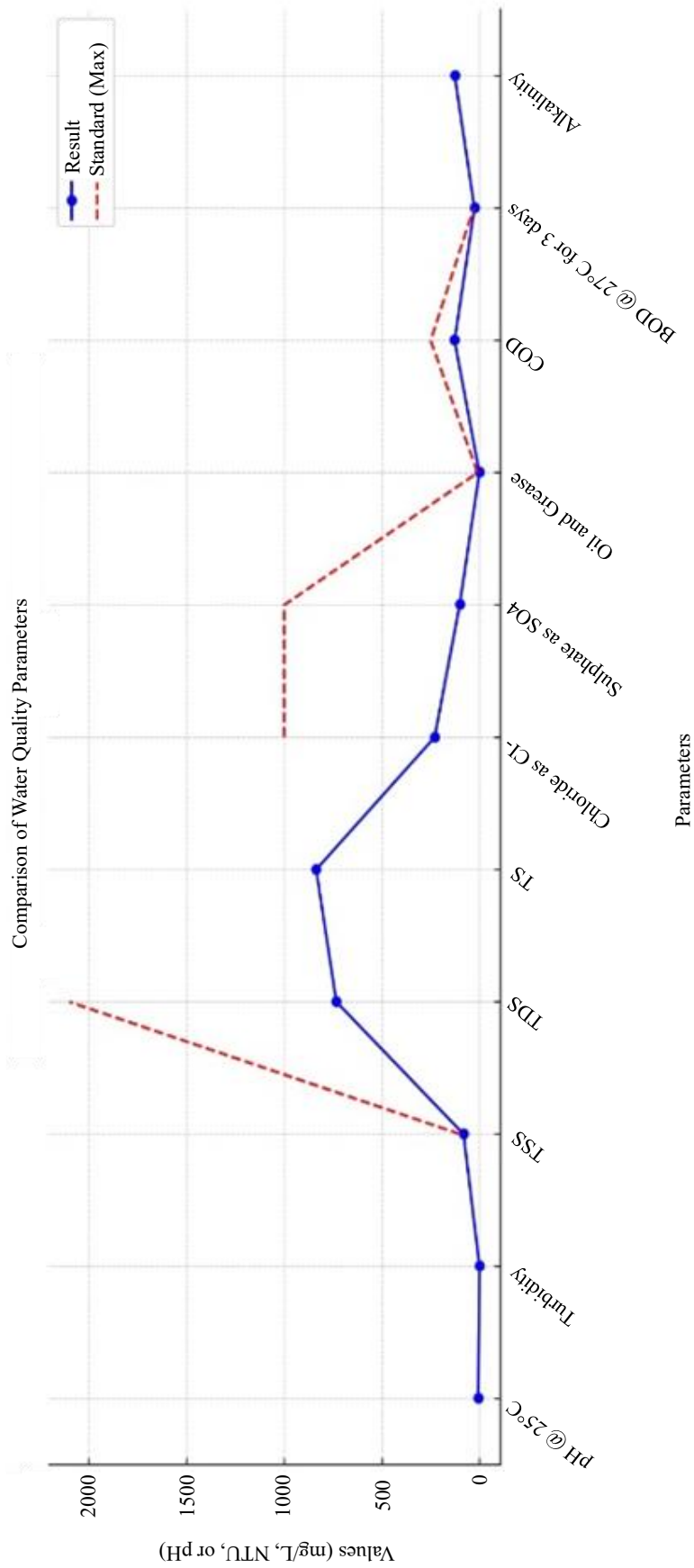


Figure 3. Performance evaluation before treatment.

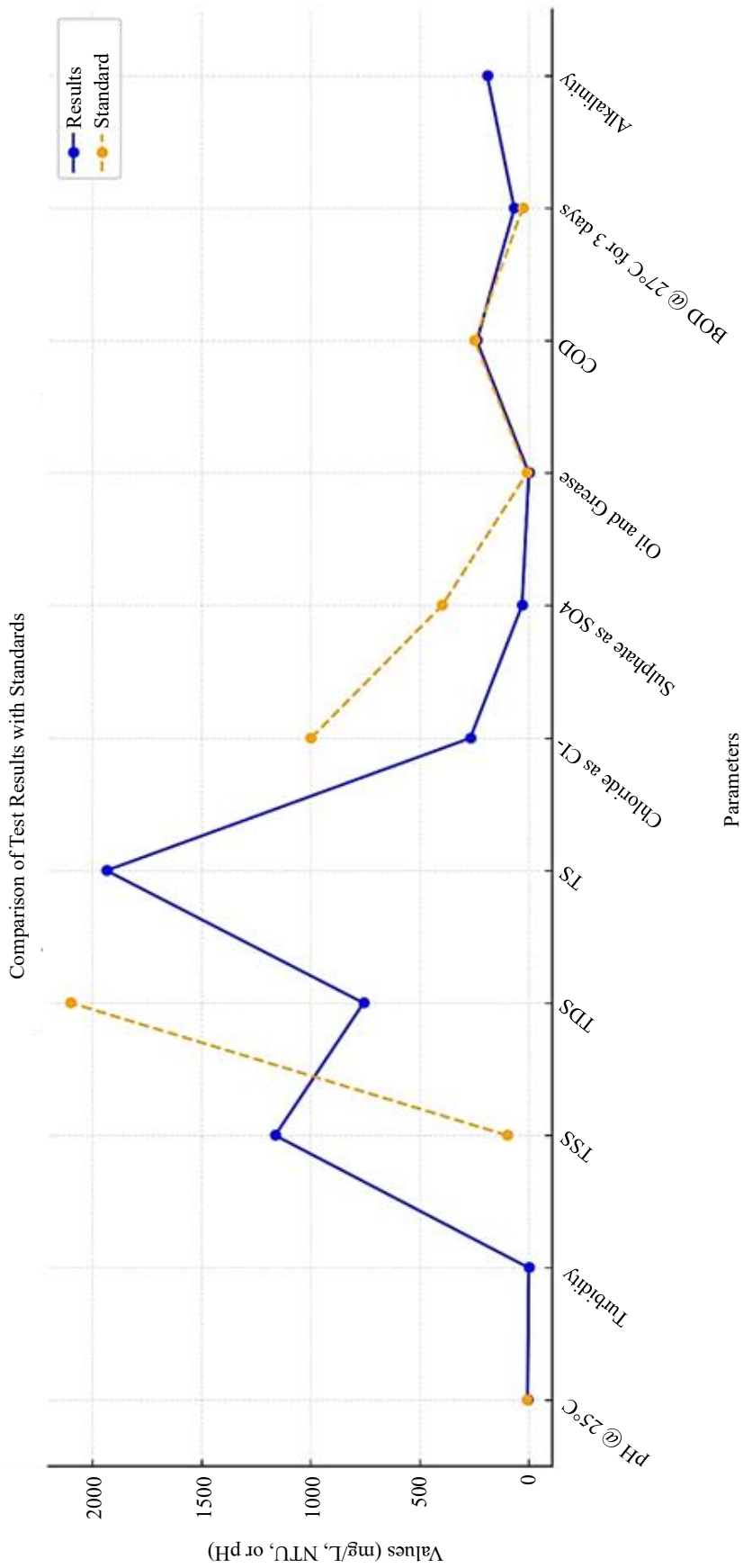


Figure 4. Performance evaluation after treatment.

The results presented in Table 2 indicate a substantial improvement in water quality following treatment with the Agave sisalana-based filtration system. Critical pollutants such as Total Suspended Solids (TSS) decreased to 82.0 mg/L, within the permissible limit of 100.0 mg/L. Likewise, Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) were significantly reduced to 26.0 mg/L and 128.0 mg/L, respectively, both now compliant with standard thresholds. Total Solids (TS) dropped drastically from 1937.0 mg/L to 836.0 mg/L, and turbidity reduced to 0.3 NTU, indicating high clarity. The pH remained stable at 7.23, and other parameters such as chlorides, sulphates, oil and grease, and alkalinity were well within acceptable limits. These improvements affirm the efficacy of the natural filter media in removing both organic and inorganic pollutants, supporting its potential for sustainable wastewater treatment. Figure 4 graphically illustrates the significant improvement in water quality parameters following treatment using the Agave sisalana-based filtration system. The post-treatment values (blue line) closely align with or fall well below the standard limits (orange dashed line) for most tested parameters. Notably, TSS, BOD, and COD, which initially exceeded acceptable levels, have been effectively reduced to within permissible thresholds, highlighting the filtration system's efficiency in removing suspended solids and organic pollutants. Additionally, reductions in turbidity, sulphates, and oil and grease further confirm the system's robust performance.

The near-neutral pH and lowered alkalinity also reflect enhanced water quality. The visual comparison reaffirms the system's sustainability. Statistical analysis using one-way ANOVA confirmed significant differences ($p < 0.05$) in removal efficiencies across different HRTs for BOD, COD, and TSS. This suggests the critical role of retention time in optimizing pollutant reduction and suitability for decentralized wastewater treatment, particularly in low-resource settings.

CONCLUSIONS

This study demonstrated the effective use of Agave sisalana fibers as a sustainable filtration medium for treating domestic sewage. Combined with silica sand and activated carbon in a vertical filter column, the system significantly reduced turbidity, total solids, BOD, COD, nitrogen, and phosphorus, with organic load removal efficiencies reaching up to 72% for BOD and 71% for COD. The novelty lies in repurposing Agave sisalana, an underutilized agro-waste, as an active filtration material due to its fibrous, porous, and lignocellulosic properties. It offers an eco-friendly, biodegradable, and low-cost alternative to synthetic or chemical media, particularly suited for rural and off-grid communities. The gravity-driven system requires no electricity, aligning with sustainable and decentralized wastewater treatment goals. For field-scale application, several challenges warrant further investigation, including hydraulic clogging risks due to biofilm growth, fluctuations in pollutant load under variable wastewater conditions, and mechanical degradation of Agave sisalana fibers over prolonged use. Pilot-scale studies should also evaluate regeneration or replacement cycles for the filter media to ensure cost-effectiveness and sustainability. This approach exemplifies circular economy practices by transforming agro-waste into a valuable filtration resource, aligning with sustainability targets such as UN SDG 6 (Clean Water and Sanitation). Future work should focus on system scaling, media reuse, and integration with other green technologies for enhanced environmental performance.

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